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Raman-Assisted Transmission of Nyquist-WDM PM-16QAM Channels at 240 Gbps on PSCF

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ABSTRACT

We evaluate by simulation the maximum reachable distance of ten Nyquist-WDM channels at 240 Gbps based on PM-16QAM in PSCF links. Operating with a channel spacing of only $1.1 \cdot R_S$ and using Raman amplification, we demonstrate a maximum reachable distance of 3,600 km. Moreover, we make an assessment of the scaling of nonlinear impairments in the case of using hybrid EDFA/Raman amplification.

Keywords: non-linear propagation, non-linear effects, coherent detection, uncompensated systems, optical transmission, DWDM

1. INTRODUCTION

In order to cope with the ever increasing capacity demand, the evolution of optical communication systems is moving towards systems with high spectral efficiency (SE): recent experiments have demonstrated a maximum spectral efficiency of 4 bits/s/Hz [1] using polarization-multiplexed quadrature phase shift keying (PM-QPSK). In order to further improve the spectral efficiency we need to resort to modulation formats with higher constellation complexity, i.e., carrying more than 4 bits/symbol. Obviously, this solution imposes a limitation in the maximum reach due to larger optical signal-to-noise ratio (OSNR) requirements and higher sensitivity to nonlinear propagation impairments. A promising candidate for SE improvement is the 16-levels polarization-multiplexed quadrature amplitude modulation (PM-16QAM) that carries 8 bits/symbol: several studies have already demonstrated its potential both through simulations [2-4] and experiments [5].

In this work, we analyze the transmission performance of ten Nyquist-WDM [6] channels based on PM-16QAM operated at 240 Gbps (symbol rate $R_S = 30$ Gbaud) with channel spacing Δf close to the Nyquist limit ($\Delta f = 1.1 \cdot R_S$). As a solution to overcome maximum-reach limitations due to higher OSNR requirements, we propose to operate on pure silica-core fibre (PSCF) links with hybrid fiber amplification (HFA) based on joint Raman and EDFA amplification. Under these conditions, we show the potential for PM-16QAM in building systems carrying up to 6 bits/s/Hz over up to 3,600 km.

2. SYSTEM AND SIMULATION SETUP

We analyze the system setup shown in Fig. 1a: a link made of N_{span} spans carrying ten PM-16QAM channels with 33.3-GHz channel spacing. Each channel is modulated at $R_S = 30$ Gbaud, corresponding to the bit rate $R_b = 240$ Gbps. This rate is derived from $R_b = 200$ Gbps for the payload plus 20% FEC overhead, so we can expect to operate the physical layer at $BER = 10^{-2}$. The corresponding net spectral efficiency considering only the payload rate is $SE = 200/33.3 = 6$ bits/s/Hz.

We consider PSCF links with a large span length $L_{span} = 120$ km. The transmission fiber is followed by a coupler enabling counter-propagating Raman pumping, a gain flattening filter (GFF) that ideally compensates for the Raman gain tilting and an EDFA with noise-figure $F = 6$ dB that recovers the residual loss. The considered PSCF characteristics are: loss $\alpha = 0.185$ dB/km, dispersion $D = 20.6$ ps/nm/km and nonlinear coefficient $\gamma = 0.81$ 1/W/km. We include 2.8 dB of extra losses due to passive components and connectors in the span. Hence we assume an overall span loss $A_{span} = 25$ dB. Optical dispersion management is absent, therefore we analyzed uncompensated links that are optimal for coherent transmission of coherently received modulation formats, including PM-16QAM [7-8].

The PM-16QAM signal is generated using a typical transmitter (Tx) based on nested MZ modulators. Each channel is optically filtered by the Tx multiplexer with a 4th-order Super-Gaussian transfer function with $BW_{-3dB} = \Delta f = 33.3$ GHz. Such filtering limits the channel bandwidth and allows for a very tight channel spacing ($1.1 \cdot R_S$) close to the Nyquist limit. The receiver (Rx), shown in Fig. 1b, includes a local oscillator (LO) that is mixed to the incoming signal in two 90° hybrids (one for each polarization). Four balanced photo-detectors (BPDs) are used to detect the signals and the outputs are filtered by 5th-order low-pass Bessel filters with $BW_{-3dB} = 0.5 \cdot R_S = 15$ GHz. The bandwidth values of the Tx optical filters and Rx electrical filters have been jointly optimized. The LO is assumed to be ideal, without phase noise. Next, two ideal electronic dispersion compensators (EDCs) based on finite impulse response (FIR) filters are applied in order to completely compensate for the link chromatic dispersion. Then, a butterfly equalizer based on 4 complex 15-tap FIR filters recovers the channel Jones matrix and compensates for residual pattern effects. The equalizer operates at

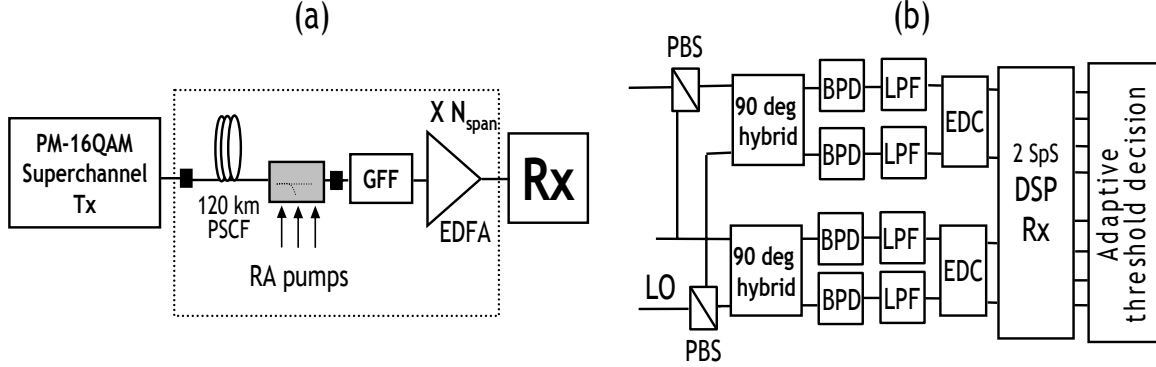


Figure 1. Layout of the analyzed system setup (a) and of the coherent DSP-based receiver for PM-16QAM channels (b).

2 samples per symbol (SpS). The filter coefficients are adjusted through a training-sequence based least-mean-squares (LMS) algorithm optimisation for initial setup and then decision-driven LMS for tracking.

Results are obtained using the OptSimTM simulator [9]: full band (600 GHz) simulations of all the 10 WDM channels spanning 2^{16} symbols (2^{19} bits $\approx \frac{1}{2}$ Mbit) per channel have been carried out for each analyzed condition. Each channel uses 8 different pseudo-random bit-sequences (PRBS) with degree = 16 for each binary bit stream. Symbol decision is done using an adaptive threshold algorithm. The bit error rate (BER) is obtained using direct error counting on the central channel.

3. ANALYSIS AND RESULTS

We first analyze the performance of Raman amplification (RA) operating jointly with an EDFA with noise-figure 6 dB for recovering the residual loss. We propose to use three unpolarized counter-propagating pumps at 1425, 1436 and 1459 nm. We consider a system scenario with overall pump power P_{pump} ranging from 200 mW up to 1600 mW. We limit the maximum overall pump power to 1600 mW in order to ensure negligible saturation effects. As a reference, we consider the case of EDFA-only lumped amplification corresponding to null Raman pumping ($P_{pump} = 0$ mW).

Therefore, we analyze propagation of 10 PM-16QAM channels over nine different system scenarios with Raman pump levels ranging from 0 up to 1600 mW, with a step of 200 mW. For each case, we vary the transmitted power per channel P_{Tx} from -7 up to +5 dBm in order to determine the optimal power level and consequently derive the maximum reachable distance L_{MAX} that still allows $BER \leq 10^{-2}$.

Fig. 2a displays the Raman on-off gain G_{on-off} with respect to P_{pump} that, as theoretically expected, is characterized by a linear dependence. The maximum value of G_{on-off} is 18.0 dB for $P_{pump} = 1,600$ mW. Fig. 2b shows the value of the equivalent noise figure F_{eq} of the HFA for the different P_{pump} levels taken into account. It can be observed that F_{eq} decreases while increasing P_{pump} : from 6 dB for the case of EDFA-only amplification it goes down to -4.0 dB for $P_{pump} = 1600$ mW. Given the system length, this result corresponds to an OSNR improvement of 10.0 dB.

Fig. 2c reports the reachable distances L_{TOT} for every value of P_{Tx} as circles connected by solid lines. Different curves refer to different Raman pumps as indicated in the plot. As a reference, reachable distances theoretically attainable with linear propagation are also reported as dashed lines. For low P_{Tx} values, nonlinear propagation results perfectly lie on the linear propagation. Increasing the transmitted power, nonlinearities become more and more relevant, clearly causing an optimal condition ($P_{Tx,opt}$) corresponding to the maximum reachable distance L_{MAX} . Beyond $P_{Tx,opt}$, nonlinearities are too strong and L_{TOT} starts decreasing.

Increasing P_{pump} , the signal propagation benefits from OSNR improvement due to lower F_{eq} , and consequently L_{MAX} increases. But the increase is partially reduced by $P_{Tx,opt}$ decreasing almost linearly from +3.0 dBm for $P_{pump} = 0$ mW down to -1.0 dBm for $P_{pump} = 1600$ mW. This is due to a stronger nonlinear impact caused by larger propagation distances and a longer fiber effective length in each span (see Fig. 3a) as a consequence of larger Raman amplification.

It can be observed that the maximum reachable distance for EDFA-only is 840 km obtained at $P_{Tx,opt} = 3.0$ dBm, while it grows up to 3600 km, obtained at $P_{Tx,opt} = -0.5$ dBm for $P_{pump} = 1600$ mW. The ratio (expressed in dB) between these maximum reachable distances is 6.3 dB. It almost matches the OSNR net improvement (10.0 dB) due to the reduction of F_{eq} minus 4.0 dB due to $P_{Tx,opt}$ lowering. The same analyses and findings apply to all considered P_{pump} values. Hence, as expected, we can conclude that the OSNR improvement can only partially be spent as an extension of L_{MAX} because of growing nonlinear effects.

In order to investigate the nonlinear impairment as a function of P_{pump} , in Fig. 2d we report the maximum reachable distance calculated in the hypothesis of linear propagation when using the optimal power $P_{Tx,opt}$

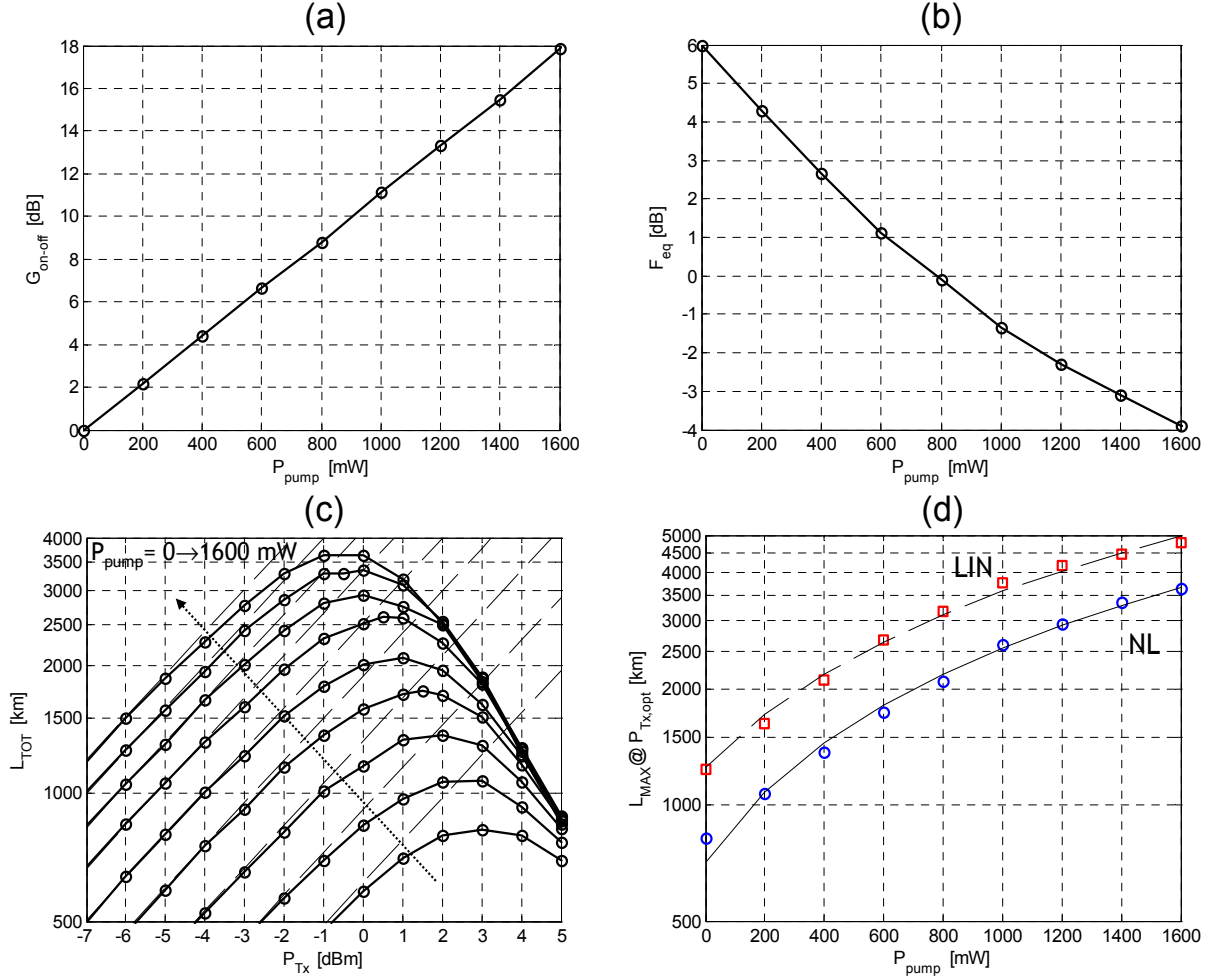


Figure 2. Raman amplifier on-off gain vs. the overall pump power P_{pump} (a). Equivalent noise figure F_{eq} for the HFA vs. the overall pump power P_{pump} (b). Reachable distance L_{TOT} @ $BER10^{-2}$ vs. the transmitted power per channel (P_{Tx}) for different levels of Raman pumping (c). Maximum reachable distance @ $BER10^{-2}$ for the optimal transmitted power vs. the overall pump power: circles are the nonlinear simulation results while the solid line is a fitting; squares are results obtained with linear propagation for the optimal nonlinear power ($P_{Tx,opt}$) and the dashed line is their fitting (d).

obtained from the nonlinear propagation analysis (square markers). We compare it with the maximum reachable distance obtained in the nonlinear regime through simulations. It can be clearly observed that the two sets of results expressed in logarithmic scale are parallel with excellent approximation: it pictorially describes that the OSNR nonlinear penalty is constant and independent of P_{pump} . If we calculate the ratio between maximum reachable distances obtained with linear and nonlinear propagation, we can numerically estimate such a nonlinear OSNR impairment: its value is about 1.76 dB (3/2 in linear scale) independent of P_{pump} . This finding precisely matches what has been found in [10] for PM-QPSK showing that modeling nonlinearity as an additive noise with respect to ASE noise is valid also for PM-16QAM.

In order to further investigate the impact of nonlinear effects on the analyzed systems, we evaluate the dependence of the effective length for a single span as a function of P_{pump} : in Fig. 3a we can see that it increases from 23.2 km at $P_{pump} = 0$ mW (intrinsic fiber effective length) up to 28 km at $P_{pump} = 1,600$ mW. Moreover, with a detailed analysis of the results we are able to show that there exists a “nonlinear invariant” independent of P_{pump} . Its expression is: $\gamma^2 P_{Tx,opt}^2 L_{eff}^2 N_{span}$ and its independence from P_{pump} is shown in Fig. 3b. This finding confirms that modeling nonlinear impairments as an additive Gaussian noise [10] can be applied also to Nyquist-WDM PM-16QAM propagation on Raman assisted links and allows us to define a more detailed expression for the nonlinear noise: $P_{NL} = \eta_{NL} \gamma^2 P_{Tx,opt}^2 L_{eff}^2 N_{span}$.

Therefore, following the method proposed in [11], the system BER is given by the equivalent OSNR, whose expression is

$$OSNR_{eq} = \frac{P_{Tx}}{N_{span} (A_{span} F_{eq} h f B_n + \eta_{NL} \gamma^2 P_{Tx}^3 L_{eff}^2)} \quad (1)$$

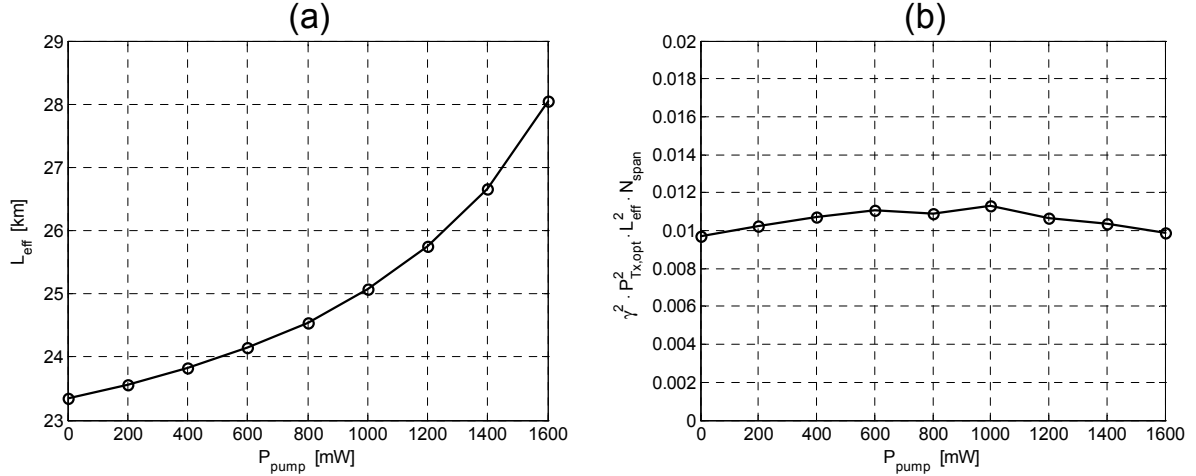


Figure 3. Effective length for a single span vs. the overall pump power P_{pump} (a). The “nonlinear invariant” ($\gamma^2 \cdot P_{Tx,opt}^2 \cdot L_{eff}^2 \cdot N_{span}$) vs. the overall pump power P_{pump} (b).

where A_{span} is the span loss, h is the Planck constant, f is the operating frequency, B_n is the OSNR noise bandwidth and η_{NL} can be determined following the method proposed in [11] and depends only on fiber parameters and on channel spacing.

Using the method proposed in [11], the maximum reach can be derived as well:

$$L_{max} = L_{span} \frac{P_{Tx,opt}}{OSNR_{eq} \left(A_{span} F_{eq} h f B_n + \eta_{NL} \gamma^2 P_{Tx,opt}^3 L_{eff}^2 \right)} \quad \text{where} \quad P_{Tx,opt} = \left[A_{span} \frac{F_{eq} h f B_n}{2 \eta_{NL} \gamma^2 L_{eff}^2} \right] \quad (2)$$

Hence, once the parameter η_{NL} is derived, system maximum reach at a given BER can be easily calculated knowing system characteristics.

4. CONCLUSIONS

We studied the potential use of PM-16QAM as a modulation format for future high-capacity systems, considering channels operating at 240 Gbps (200 Gbps for payload + 20% FEC overhead) tightly spaced by only 33.3 GHz, corresponding to 1.1·Rs. We analyzed propagation over PSCF with a 120-km span assisted by hybrid Raman/EDFA amplification. We demonstrated that using 1,600 mW of Raman pump the maximum reachable distance at BER = 10⁻² is 3,600 km, obtained with P_{Tx} = -1.0 dBm. Moreover, we showed that nonlinear impairments can be modeled as an additive noise also when employing PM-16QAM and Raman-assisted links. Finally, we derived a more detailed expression for the nonlinear noise based on a single fitting parameter depending only on fiber parameters and channel spacing.

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